FLUID PHYSICS Case Inst. of Tech.

Semi-Annual Status Report of Research Performed under NASA Grant NGR-36-003-064 for the Period June 1, 1965 to November 30, 1965.

This grant is for research in a general field. The work is being carried out in various problem areas and will be reported in that way herein.

I. HYDRODYNAMIC STABILITY **NASA CR 71008**

1) Stability of Two-Fluid Wheel Flow.--A wheel flow gaseous nuclear rocket has been proposed (Evvard, NASA TN D-2951, 1965) wherein the heavy gaseous fissionable material in the interior is surrounded by a light gas propellant. Energy transfer to the propellant is hopefully by thermal radiation from the hot fissioning fluid. Such a configuration is however unstable to infinitesimal disturbances. Calculation of the growth rates by Reshotko and Monnin (NASA TN D-2696, 1965) for the idealized case of inviscid immiscible incompressible fluids yield the physically implausible result that for large wave numbers (small wavelengths) the growth rates continue to increase with increasing wave number. It is felt that the small wavelength disturbances should be damped due to viscous dissipation.

Two analyses are in progress. The first considers the effect of viscosity on the growth rates of the helical disturbances. The analysis is being carried out by an asymptotic technique. The eigenvalue problem has been formulated and first numerical calculations are in process. The second analysis treats the effect of surface tension at the fuel-propellant interface. This analysis is most appropriate to a propellant in the liquid state. It is shown that even in the absence of viscosity, the effect of surface tension is to damp disturbances having larger than a critical wave number. More specifically for disturbances of the form

$e^{i(kz + m\theta - \omega t)}$, damping occurs for

$$m^2 + k^2 - 1 > \frac{\rho a^3 \Omega^2}{\sigma}$$

where k is the axial wave number, m is the azimuthal wave number, ρ is the density of the heavy fluid, a is the radius of the heavy fluid column, Ω is the angular velocity of the wheel flow and σ is the surface tension.

The analyses will be extended to consider the combined effect of surface tension and viscosity.

2) Stability of Magnetohydrodynamic Configurations.--The disturbance equations for incompressible parallel flows in an electrically conducting fluid have been derived for flowing, current-carrying configurations. These equations include effects of finite viscosity and resistivity and are applicable to channel flows, boundary layer flows and sheet pinch configurations. With the aid of an energy relation, the results can be used to determine the mechanism of instability pertinent to each case.

Results for the case of plane Poiseuille flow with coplanar magnetic field have just been reported. (Nachtsheim and Reshotko, NASA TN D-3144, 1965). These show in detail the effect of magnetic Reynolds number on the relative importance of the Maxwell stresses and joule dissipation as well as Reynolds stress and viscous dissipation. The next cases of interest are the sheet pinch and accelerator or generator boundary layers.

II. STUDIES OF NON-HOMOGENEOUS FLOWS

1) Seeded Gas as a Mixture of Two Diffusing Species.--An intensive study has been carried out on treating a seeded gas as a mixture of two

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diffusing species. Diffusion due to pressure gradient is retained since it becomes very important in rotational flows. The low seeding concentration attainable in practice is kept constantly in mind. The consequential low conductivity is taken advantage of in the analysis in neglecting the induced magnetic field. It is planned to apply this general formulation to specific practical situations. The one situation now under numerical studies is the vortex-type MGD generator. In the past, such a generator was always analyzed with the assumption of uniform seeding concentration. In view of the rotation and the large molecular weight of the seeding vapor, this assumption is far from realistic. A re-study under the present scheme would prove invaluable. The governing equations are already set up. A programmer will soon be engaged in the numerical part of the study.

Other problems contemplated up to now are: Cooling of electrodes by injecting seeded gas. Jet-mixing of seeded gas in a moving stream. Study of the linearized problem. All of these problems have been under preliminary studies, and have been judged most interesting. It is quite clear now that this study will warrant continued effort in the future.

2) Effect of Suspended Particles in a Fluid Flow.--

a) Compressible Rayleigh's problem with frozen solid particles and negligible heat transfer.--It is found that under certain limiting values of various parameters, the solid particles become in effect frozen in space with negligible heat transfer between the particles and the gas. For such a case, the compressible Rayleigh problem can be solved asymptotically for large time. A Kármán-Pohlhausen-like technique has been used in the solution. Numerical work has been completed. A comprehensive report will be submitted soon.

b) Momentum and thermal response of solid particles in parallel flows.--This task belongs to what is usually called elementary problems. It is taken up, because as usual, these problems throw much light on the inner structures of the phenomena under investigation without undue labor. In the present case, it is to be especially noted that the responses can be investigated for any values of the velocity and temperature equilibration lengths.

The problems treated in this task are:

(i) Momentum or thermal response to a sudden change of velocity or temperature of an infinite flat wall.

(ii) Thermal response in a slug flow in a channel, on entering a heated region. Axial conduction is <u>not</u> neglected.

(iii) Momentum response to an oscillating wall.

(iv) Momentum response to a oscillating pressure gradient.

All of these are solved exclusively by suitable integral transforms. Problem (ii) is attacked by an unusual application of the technique of integral transforms suggested by P. C. Lu. Numerical work is now under way. This task is considered essentially finished. A complete report will be submitted later.

III. HIGH-SPEED LUBRICATION

1) A Critical Review of High-Speed Lubrication Theory.--A review of the literature on the theory of high speed lubricant flows was completed, and the results of this survey are being prepared for publication. This work should prove useful in determining the direction of future research efforts.

2) Velocity Distributions in Journal Bearings at Moderate Reynolds Numbers.—A study of the laminar velocity profiles for infinite, full cylindrical journal bearings at small eccentricity was made in which the modified or lubrication Reynolds number was varied from its classically low value of order 10^{-3} to 10^{2}. The results of this study have been prepared for publication and should prove helpful in a basic understanding of the transition from low modified Reynolds number to moderate modified Reynolds number flow regimes.

Presently, an effort is being made to determine the effect of item 2) above on the behavior of the flow in the neighborhood of the Taylor stability boundary.

IV. INTERNAL FLOWS

1) An Equitriangular Transform and Its Applications.—In a search for integral transforms useful in solving boundary value problems in an equilateral triangular region, it is found that a set of eigen-functions exists for the Helmholtz boundary value problem of the first kind. The set is orthogonal but not complete. If we supplement it with the still unknown set $\{\phi\}$ to make it complete, an integral transform, called an equitriangular transform, can be devised. It is then noted that for a large class of problems with zero boundary values and constant inhomogeneous terms, the unknown set $\{\phi\}$ does not enter; and the problems are solvable by this transform in terms of the known set only.

This discovery is then applied to the following physical problems of interest (all in an equilateral triangular pipe):

(1) Steady and unsteady viscous flow (and, heat conduction in an equitriangular column).

(2) Steady combined free and forced convection flow.

(3) Commencement of free convection flow.

(4) Transient response of suspended particles in a viscous flow.

Numerical calculation has been done extensively for the most practically interesting cases.

This task has been successfully concluded. A comprehensive report will be submitted in the near future.

2) The Dynamics of Slinger Seals.--A detailed study of the laminar flow of engaged fluid between a rotating disk and a stationary housing is underway with the spacing between the disk and housing as a parameter. Results are available for narrow spacing (almost fully developed) and for large spacing (boundary layer approximation). Torque, pressure ratio and heat transfer information is being prepared for these limiting cases.

Attention is now being given to the integrity of the interface between fluid and vacuum.

3) Flow in Parallel Heated Tubes.--Heated reactor passages in laminar flow have long been regarded as being unstable in that region of operation where the rate of change of pressure drop with weight flow at constant heat input is negative. This criterion has so far not been supported in the literature by any stability analysis. Such an analysis has been undertaken and completed. The results show that the instability is not a flow instability but rather is associated with the thermal response of the reactor core to an infinitesimal disturbance. An abstract of a paper describing the analysis and results has been submitted and accepted for presentation at the forthcoming Propulsion Joint Specialists Conference to be held in June, 1966.

The parts for an experimental apparatus to study this stability phenomenon are arriving and the assembly should begin in February 1966.

4) Analysis of Laminar and Turbulent Flow in a Diverging MHD Channel.—During the reporting period attention was focused on three aspects of the problem:

1. Effect of decreasing mean flow velocity on two-dimensional "Hartmann-like" flow. The equations have been formulated and calculations will be carried out in the near future.

2. Effect of Lorentz force on laminar boundary layer development on the electrode wall. The specific objective here is to investigate the effect of the Lorentz force on laminar separation.

3. Prediction of turbulent flow losses in MHD channels. Here experiments of Moszynski (to be published) and those of Lykoudis and coworkers indicate that satisfactory predictions may be obtained with the aid of ordinary friction factor correlations. Detailed calculations are in progress.

V. EXTERNAL FLOWS

1) Boundary Layer Development About a Yawed Cone.—The laminar boundary layer about a circular cone in supersonic flow at large yaw angle has been studied by F. K. Moore, Reshotko, Brunk and Cheng. These studies yielded results only in the plane of symmetry and more specifically on the windward side. The present study considers the boundary layer development about the cone away from the most windward streamline.

With the tentative assumption that at the angles of attack of interest, the streamtubes entering the boundary layer all come through the most windward portion of the conical shockwave, the boundary layer equations have been formulated. They seem to admit of similarity solutions. A machine program is being formulated to obtain the similarity solutions. The results when obtained will be compared with the recent experimental data of Tracy at Caltech.

2) Investigation of Turbulent Boundary Layers with Transpiration.-- During the reporting period, primary attention was focused on assembly of the high temperature wind tunnel and installing the basic instrumentation. The former has now been essentially accomplished, the latter is still in progress.

Specifically a gas burner ring has been fabricated and installed in the pipe leading to the settling tank. A control system for ignition and emergency shut-off has been designed and components purchased. The test section with variable nozzle and flexible upper wall has been assembled and its mechanical operation has been tested. The entire piping system has been completed.

It is planned to complete low temperature calibration runs before the end of March 1966, following which the entire tunnel with its drive will be transferred to the Bingham Building, pending construction of the new Engineering Building.

A study of available experimental data has been continued in order to aid in the planning of a rational program of experiments. As a result of this study it has been decided to investigate initially the structure of incompressible boundary layers with relatively high blowing rates and favorable pressure gradients. These conditions will provide a rather severe test of the validity and limits of applicability of the velocity defect law.